Results and Discussion

Body shapes obtained by subjecting the class of shocks obtained as a solution in Ref. 1, to the inverse procedure of Maslen, agree very closely with the body shapes with which[1] it started. However, as anticipated, the pressure distribution along the body surface is different. Though for low shock curvature (lower value of a) the pressures are lower than those given by HSDT, for the higher curvature ($a=1$), the induced pressures are higher than in Ref.1. It would appear that there exists a critical curvature corresponding to some value of a between 0.1 and 1 at which the pressures calculated by the two methods would compare.

For a qualitative comparison, the pressures calculated using the modified Newtonian formula $C_p = C_p^* \sin^2\theta_b$ have also been shown in Fig. 3. For the higher curvature, the pressure so calculated predicts higher values than by the HSDT, as does the present analysis. As a further check, the body surface pressure is obtained using the laminar layer model.[3] Here, an impulse function Q is defined as

$$Q = \int_0 \cos\theta \, d\psi$$

which leads to

$$C_p = 2\sin^2\theta + 2\sin\theta\cos\theta \frac{d\theta}{dQ} \tag{12}$$

Applying this to an exponential shock, and interpreting the pressure as the sum of the Rankine-Hugoniot pressure immediately behind the shock and a centrifugal correction term, leads to the expression

$$C_p = c_p^* \{ \frac{A^2 e^{2aZ}}{1 + A^2 e^{2aZ}} + \frac{A\, e^{aZ}}{(1 + A^2 e^{2aZ})^{3/2}} \times \ln[\frac{A\, e^{aZ} + (1 + A^2 e^{2aZ})^{1/2}}{A + (1 + A^2)^{1/2}}]\} \tag{13}$$

where $C_p^* = 4/(\gamma+1)$. This has been plotted in Fig. 4, which also gives the corresponding Maslen pressures. The agreement is excellent.

Conclusions

Exponential shock waves supported by 2-dimensional bodies concave to an oncoming hypersonic stream, for $M_\infty \to \infty$ and $\gamma = 1.4$ have been analyzed using the inverse method of Maslen. The body shapes obtained agree well with those given by the HSDT. The Maslen pressures along the surface of the body are higher than those predicted by HSDT, for higher shock curvature. These pressures agree excellently with the pressures calculated using the laminar layer model. A case exists for analyzing in detail the pressures for various nose bluntnesses, as it would help in better drag optimization studies on aerofoils.

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Airframe Noise—The Next Aircraft Noise Barrier

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Introduction

PROGRESS in quieting the commercial aviation fleet has been achieved in recent years by reducing the noise generated by turbofan engines on new aircraft. This has been achieved by using higher bypass ratio engines that reduce jet exhaust noise and the application of noise treatment in fan ducts to contain turbomachinery noise. Further technology advancements are expected to make possible additional engine noise reductions. However, further improvements in engine noise reduction mean that nonengine noise sources may become important. References 1 and 2 were among the first in which it was noted that nonpropulsive aerodynamic noise (subsequently referred to as airframe noise) would become the dominant noise source during approach to landing for conventional aircraft designs in which the engines have been quieted to meet more stringent certification requirements. This Note addresses the scope and significance of airframe noise as a new problem in aircraft design by reviewing the present state of the art for its understanding and prediction.

Sources of Airframe Noise

The individual noise sources that combine to produce overall airframe noise of a landing aircraft are illustrated in Fig. 1, and most have been discussed in detail in the literature.[1-4] The main contributors are the turbulent boundary layer; the flow over the extended landing gear, wheel well doors, and wheel well cavities; the flow about the extended flaps and slats; and the wake vorticity associated with lifting surfaces and fuselage. The radiated noise is highly dependent on details of the local flow and, thus, is very configuration dependent.

When a vehicle is aerodynamically "clean," that is, with flaps and gear retracted, the dominant airframe noise is associated with fluctuating lift and drag forces on lifting surfaces. Such unsteady aerodynamic forces can arise from inflow turbulence, from the boundary layer, or from the turbulent wake interacting with the surface. Present estimates are

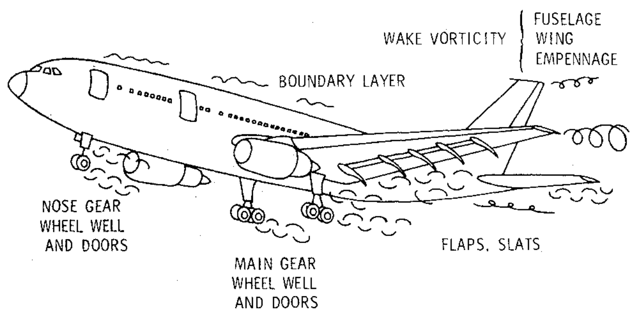

Fig. 1 Airframe noise sources.

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that the dominant clean airframe noise source is the turbulent wake interacting with the airfoil to generate fluctuating lift and drag forces on the whole surface (which produces low-frequency noise) and to generate small-scale pressure fluctuations at the trailing edge (which produces high-frequency noise).

When aerodynamically "dirty," with landing gear, flaps, and slats deployed, the dominant noise source will depend on the local flow about these protuberances. Of course, the flaps are lifting surfaces and subject to the same mechanisms just mentioned for wings but with the added complication that wake turbulence of upstream airfoils becomes inflow turbulence for trailing surfaces. Separated flows around landing gears and over wheel well cavities can be very large noise sources and can dominate for some configurations. Generally, aerodynamic noise is generated by anything that creates turbulence or separated flows.

Airframe Noise Prediction

A great amount of research has been accomplished on the general problem of noise generation of aerodynamic flows interacting with surfaces. However, the prediction of airframe noise for a complete aircraft has only begun to be considered. The engineering methods available now are largely empirical and, while useful, must be applied with care.

Aerodynamically Clean Configurations

The best-known procedure for predicting airframe noise has been reported by Gibson[1] and has since been updated by Healy.[5] Based on flyover noise measurements of five aircraft with power off, they assume the dominant noise source to be a dipole resulting from fluctuating forces oriented parallel to the lift vector. Their prediction for the far-field noise directly beneath the aircraft is

$$\mathrm{OASPL} = 10 \log_{10} [V^6 S / r^2 A^4] + K_1 \qquad (1)$$

The velocity to sixth power dependency (V^6) and inverse square dependence on distance (r^{-2}) result from the assumptions of a dipole source and far-field observation. The dependence on surface area A, aspect ratio A, and the constant K_1 have been determined from experimental data. It is indicated in Ref. 5 that this equation fits the measured clean airframe noise data for the five aircraft considered with a maximum deviation of less than ± 3.0 db and an average deviation of $+1.0$ to -1.5 db. Its predictive capability for conventional subsonic aircraft configurations of moderate to high aspect ratio is demonstrated in Ref. 6 wherein the OASPL for the C-5A was within 0.6 db of the measured value. However, caution must be used in applying the equation to configurations dissimilar to those in the original data base. For instance, an overprediction of about 20 db in OASPL when applied to a delta wing supersonic vehicle is cited in Ref. 7.

More recently, a related empirical equation for clean airframes (i.e., flaps and gear up) has been developed in Ref. 8. In addition to the data base used to develop Eq. (1), other published data as well as unpublished data from airframe noise tests on several additional commercial jet transport vehicles were used.

A linear regression analysis was applied to a data base of 53 OASPL measurements to obtain the following predictive equation

$$\mathrm{OASPL} = 10 \log_{10} \left[\frac{V^{3.17} W^{0.88}}{r^{1.62} S^{0.16} A^{2.06}} \right] + k \qquad (2a)$$

when W is the aircraft weight. Assuming equilibrium flight, weight will be proportional to $V^2 S$ so that Eq. (2a) may be written as

$$\mathrm{OASPL} = 10 \log_{10} \left[\frac{V^{4.93} S^{0.72}}{r^{1.62} A^{2.06}} \right] + K_2 \qquad (2b)$$

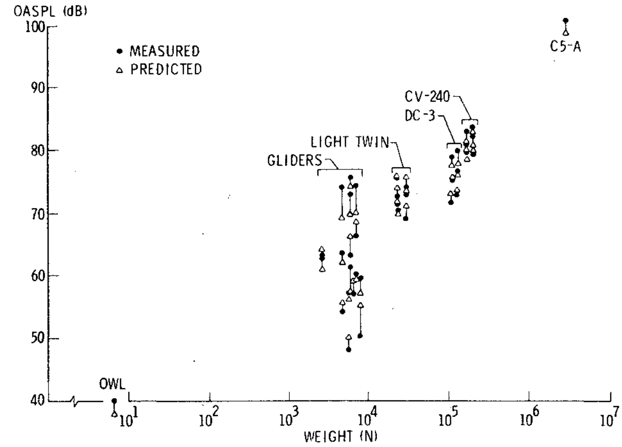

Fig. 2 Clean airframe noise levels.

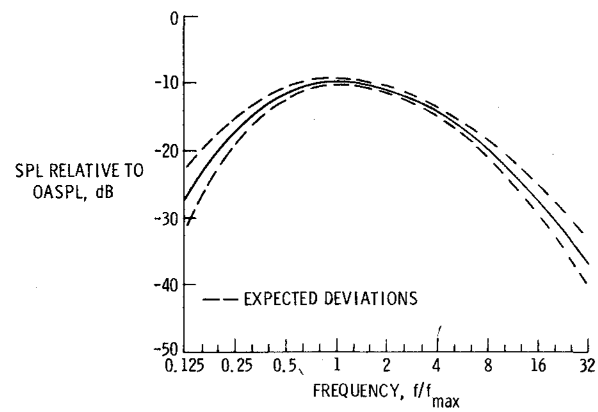

Fig. 3 Nondimensional airframe noise spectrum.

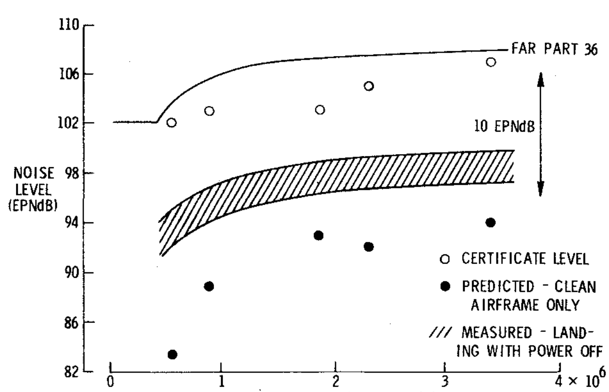

Fig. 4 Approach noise of current aircraft.

The parameters are the same as in Eq. (1) but the exponents, as determined by the statistical procedure to minimize error, are quite different from the integer values in Eq. (1). Whereas Eq. (1) was derived by assuming the noise varied as velocity to the sixth power, this result indicates a fifth-power velocity dependence. In addition, attenuation of noise with distance is less than would be predicted by the inverse square law ($r^{-1.62}$ instead of r^{-2}) indicating noncompact sources or measurements made within the near field.

The ability of Eq. (2) to predict the airframe noise of a wide variety of configurations is shown in Fig. 2. Both measured and calculated OASPL's are shown as a function of vehicle weight. The measured data points are part of the 53 measurements used in the original regression analysis. The calculations match the measurements with a root-mean-square error of 2.9 db and do even better (an rms error of 1.4 db) if the glider data, taken several years ago, are not considered in the regression analysis. The most impressive feature of this prediction is its applicability over a weight variation of six orders of magnitude.

It should be reiterated that this correlation is for conventional aircraft designs of moderate to high aspect ratio in the cruise configuration. As such, this equation predicts the noise "floor" for aircraft with today's technology. That is, it represents the minimum power-off noise that can be achieved by simple aerodynamic cleanup.

These empirical predictions of OASPL directly beneath an aircraft during flyover give no information about the frequency content of the observed noise. However, Healy[5] used smoothed spectra from clean configured aircraft to define the nondimensional noise spectrum illustrated in Fig. 3. He suggests that the frequency at which the spectrum peaks can be determined from a Strouhal relation, leading to the equation

$$f_{\max} = 1.30(V/t) \tag{3}$$

where V is velocity, and t is a representative wing thickness taken at the wing station whose chord is equal to wing area divided by wing span. The dashed curves in Fig. 4 are the boundaries within which his measured data fell. More recently, Ref. 6 has presented some data on a very large aircraft (C5-A) wherein the spectrum peak was found to be narrower although the frequency at which the peak occurred agreed reasonably well with this prediction.

Landing Configurations

The approaches just discussed assumed that airframe noise would be very configuration dependent for aircraft on landing approach due to flaps and landing gear exposed to the airstream. Therefore, to account for "dirty" configuration noise generation, both Healy and Hardin suggest that the OASPL predicted for clean airframes be increased by 5-6 db. This factor was found by both investigators to predict the landing configuration noise within the accuracy expected for preliminary design purposes, and required no additional information about the aircraft under study.

Recently, Revell[9] has proposed an alternate predictive scheme that directly predicts airframe noise of any configuration if its drag parameters are known. He bases his semiempirical theory on the assumption that airframe noise is a byproduct of mechanical energy dissipated by drag. He then uses the spectral sum of three assumed major sources of dipole noise: 1) wing profile drag, 2) wing induced drag, and 3) fuselage and landing gear drag, to arrive at a predictive equation of the form:

$$\text{OASPL} = 10 \log_{10}[C_D^2 V^6 S/r^2] + K_3 \tag{4}$$

Both similarities and differences to Eqs. (1) and (2b) are apparent. For instance, for a clean lifting wing where induced drag produces the dominant noise and $C_{Di} \sim 1/A$, this procedure would predict the same dependence on aspect ratio as Eq. (2b). The spectrum employed in this approach is more complicated than the generalized spectrum used by the earlier methods (Fig. 3) since each of the three drag components contributes. Although this method has only been applied to a limited number of cases, it promises to be very useful since readily available drag data are sufficient for its application.

Results

The ability of these methods to predict the approach noise of commercial-type aircraft at the FAR Part 36 measuring point is illustrated in Fig. 4. Approach noise, in EPNdb, is shown as a function of gross take-off weight for several aircraft. The open symbols represent the certificated noise levels for the latest generation aircraft and are all below the FAR Part 36 standard. This measured noise consists of the summation of noise from all sources on the aircraft, but engine noise dominates. The method of Hardin, Eq. (2b), was used to predict the clean airframe noise, indicated by the closed symbols. Effective perceived noise level values were estimated assuming a level flyover at approach velocity, dipole directivity, and the predicted OASPL level and the nondimensional spectrum given in Fig. 3. These values are seen to be about 15 EPNdb, on the average, below the certificated noise levels. Since the aircraft are in the approach configuration, 5-6 EPNdb must be added to the calculations to account for noise generated by "dirty" aerodynamics associated with flaps and landing gear. This brings the total airframe noise for these aircraft to the level indicated by the dashed area, approximately 10 EPNdb below the FAR Part 36 standard. The prediction method of Revell, Eq. (4), is also reported in Ref. 9 to predict an airframe noise level about 10 EPNdb below those specified in FAR Part 36. The credibility of these predictions is enhanced in Ref. 2 which reported engine-idle flight tests with B-727 aircraft that established their approach airframe noise levels at the certification measuring point as about 8 EPNdb below the FAR Part 36 standard.

Figure 4 shows that engine noise must be reduced another 5-8 EPNdb in the current generation aircraft before airframe noise becomes a significant factor in certification measurements. But it also shows that, if engine noise could be reduced still further, about 5-6 EPNdb of airframe noise reduction could be achieved by working on aerodynamic cleanup before hitting the clean airframe floor. Thus, the first payoffs in airframe noise reduction can be up to about 5 EPNdb by reducing the noise generated by flows around flaps, landing gear, and cavities.

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Propulsive Effects due to Flight through Turbulence

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Introduction

THE production of thrust on an airfoil subject to an oscillating airflow has been called the "Katzmayr Effect."[1] Flight through random turbulence would be expected to produce a similar propulsive effect,

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